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SPEED CONTROL OF INDUCTION MOTORS
FOR
ROLLING MILL SERVICE

By

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A Thesis Submitted for the Degree of
BACHELOR OF SCIENCE
Electrical Engineering Course

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INTRODUCTION

The time has gone by when it was necessary to discuss the advantages of the induction motor for rolling mill service. Time and experience have long since proved these beyond reasonable doubt. Nevertheless, there are a great many problems concerned with its application which are not yet fully solved. One of these is concerned with the provision of suitable and adequate speed control. Owing to the fact that this type of motor is inherently a constant speed machine it is not readily adapted to multispeed service, and for this reason its field of application has been restricted to that of constant speed work. In spite of the short-comings of the induction motor in this respect it still possesses many of the features and characteristics so desirable for rolling mill drive; and for this reason renewed effort has been made on the part of engineers during recent years to make up its deficiency and thus further its scope of application. Not only has the subject of multispeed control for induction motors been more or less constantly agitated thru the technical press and discussed with more or less detail at the meetings of the various industrial societies, but a vast amount of valuable data and information has been obtained as a result of many elaborate and costly experiments carried on in conjunction with actual rolling mill practice. Out of these discussions and experiments have evolved a great many schemes, each a compromise, to further the solution of the adjustable speed problem. Altho many of these arrangements

have certain objectionable features which have precluded their general adoption for practical use, yet the importance attached to many of them, especially to the more recent ones, is only indicated by the almost promiscuous use to which the induction motor has been placed during recent years.

Because of the growing importance of the subject dealing with the general control of the induction motor for multispeed work and in view of the absence of material in available form on this subject there is a need for the collection and arrangement of such material. To fill this end the work of this thesis was undertaken.

It shall be the purpose of this thesis to unify and correlate, in as simple and untechnical manner as possible, the existing material dealing with the economical speed control of the induction motor as applied to rolling mill service. The plan of treatment in this discussion is, (1) to review briefly some of the methods most commonly used, not only in rolling mill work but in the allied industries as well, for controlling the speed of induction motors, (2) to discuss those speed regulating sets, both early and recent, which employ three-phase commutating regulating machines in conjunction with the main induction motor, and (3) to consider the essential features in the construction and operation of the standard arrangements used for automatically starting induction motors, both of the form-wound and squirrel-cage rotor type.

CHAPTER I

Common Arrangements

General: For general induction motor service requiring moderate capacity and reasonably constant speed range there are a number of simple and satisfactory arrangements which may be used to control the speed of an induction motor. Each of these systems has its own peculiar advantages and limitations, and for this reason no one of them can satisfy all conditions of practice. Because of this peculiar diversity of characteristics and field of application of the various methods classified under this chapter, each method can best be considered separately and in the order of its simplicity.

Rheostat or Secondary Control: The simplest method of reducing the speed of an induction motor is, of course, obtained by the use of a wound rotor provided with slip rings between which a variable resistance is connected. By means of this resistance any speed required, within a limited range, may be obtained for a definite load and with a corresponding loss of efficiency depending on the load and reduction in speed. By properly proportioning this rotor resistance, the starting current or the starting torque may be adjusted to any required value; and by properly designing the resistance steps, so that they they can be cut out gradually, the motor can be made to pass thru a series of speed-torque curves similar in form to those shown in figure 1. Here are shown the conditions for

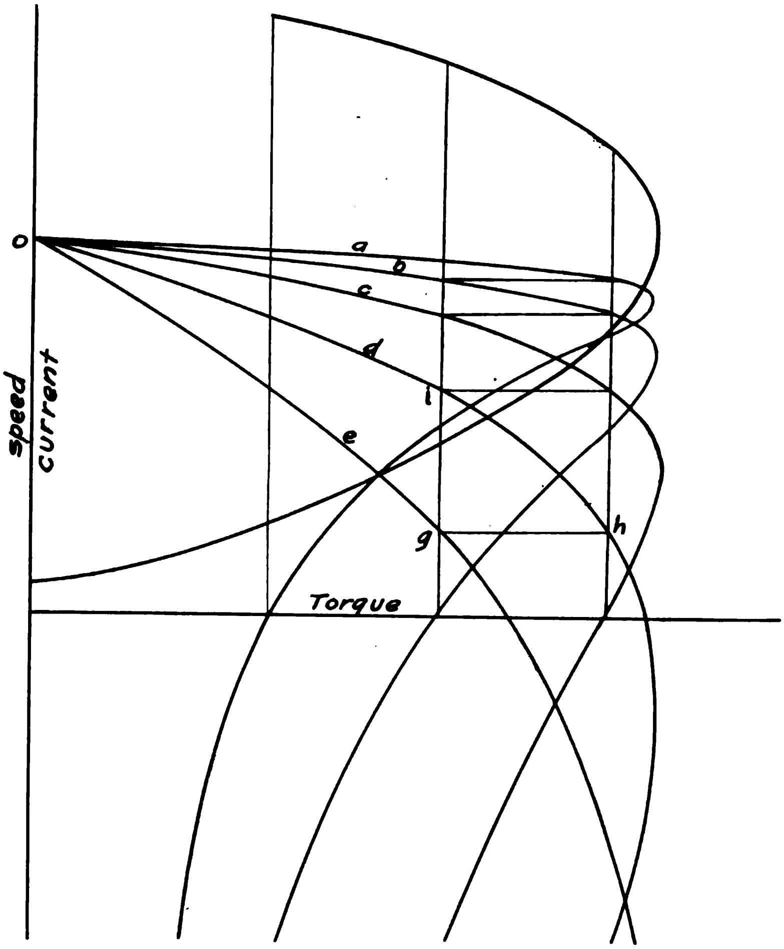

Figure 1.

starting and speeding up when five steps are provided in the rotor resistance. The motor is started at the point f on curve e, and the speed rises to point g. More resistance is cut in and the speed of the motor rises from point h to point i on curve d. In a similar manner the speed of the motor follows successively curves c, b, and a, as more resistance is gradually cut in, until the rotor is finally short circuited and the full speed point, o, is reached. It should be noted that the starting current follows one curve for all values of resistance and at no time reaches very high values.

With simple rheostat control we are limited, however, by the speed variation which occurs with varying load, because at light loads the speed of the motor will rise to its maximum value no matter what the full load may be. Within certain limits —where the regulation does not vary more than from 10 to 15 per cent from synchronous speed— the rheostat method of control is not only the simplest and most satisfactory, but, under many mill operating conditions, it is also the most economical. This may not at first be evident, but it must be remembered that in that class of mills requiring speed requlation, the load is usually comparatively constant due to the fact that there is often more than one piece of metal passing thru the rolls simultaneously. Furthermore, the intervals between passes is usually relatively short, so that on the whole the actual speed variation is not so great as may thot would be the case. This is especially true if the fly-wheel effect is at all appreciable.

Without automatic regulation of the resistance, about 15

per cent regulation is the maximum that is possible to obtain under normal operating conditions. However, if some method is employed whereby the resistance may be automatically regulated inversely with the load, it is usually practicable to obtain a speed variation of about 30 per cent. Beyond this limit it is hardly practical to use rheostat speed regulation, altho up to 30 per cent this method gives fairly satisfactory results.

The rheostat method can be used to advantage in service where reduced speeds are required only occasionally and for short durations, and where slight variations in speed are not objectionable. On account of the large amount of energy lost in the resistors the efficiency of the motor is reduced at low speeds -- this reduction being greatest at the slowest speeds — so that this method is not well suited to continuous operation much below synchronous speed.

Primary or Voltage Control: The speed of an induction motor may be changed by variation of the voltage impressed on the stator, or primary, of the motor by means of adjustable resistors, auto-transformers, or choke-coils placed in series with the circuit. This method, obviously, has a limited range in as much as the torque of an induction motor varies as the square of the impressed voltage for any given slip. The advantage of this method centers in the possibility of using the squirrel-cage rotor and its simple resistance controller. A squirrel-cage rotor designed for this service, however, is expensive because its resistance must be high in order to obtain a reasonable variation. High resistance increases the rotot losses and requires a large motor

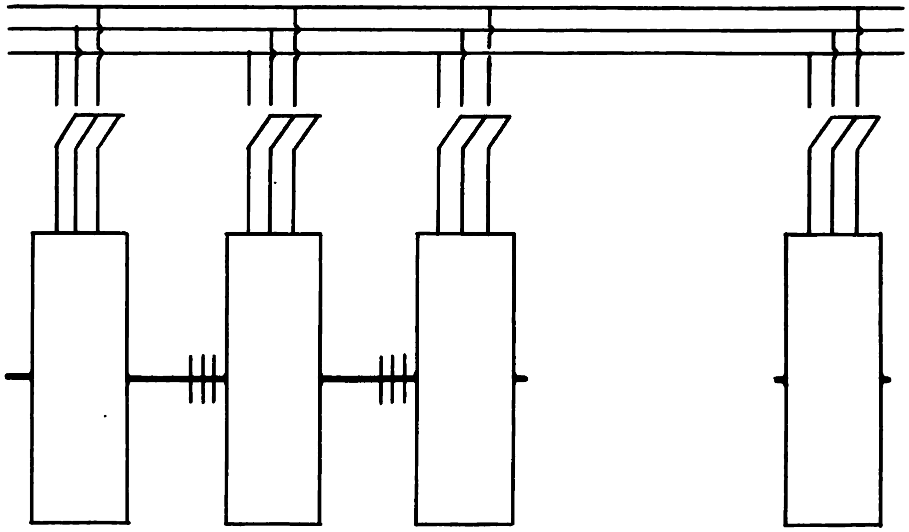

Figure 2.

in order to maintain the temperature at reasonable limits. Furthermore, compensators are complicated and expensive in as much as they cannot be short circuited, as can resistors, but must be cut out by means of additional auxiliary apparatus. Compensator control is more efficient and draws a smaller current than resistance control, but it has a poorer power factor.

The primary voltage method of speed control, then at the best, has all the disadvantages attending poor speed regulation, low efficiency, poor power factor, and unsatisfactory control in general, especially in cases where the voltage is high. With all these disadvantages it is not surprising, then, that this method of control has not met with more popular favor. It might be mentioned, however, in this connection that squirrel-cage induction motors are almost invariably started with reduced voltage by means of compensators.

Frequency Changers: For adjustable speed work where large speed ranges are not required and where frequent changes are not necessary a simple method may be used to vary the speed of an induction motor. This method operates on the basic fact that the speed of an induction motor varies in direct proportion with the frequency of the supply voltage. So that, by varying the frequency of the supply voltage, theoretically, any speed may be obtained. There are various methods for utilizing this principle all of which are characterized by high first cost.

The simplest arrangement would be to use a set similar to the one shown diagramatically in figure 2, consisting of an alternating current motor and the requisite number of generators for the various frequencies. This system is little used on

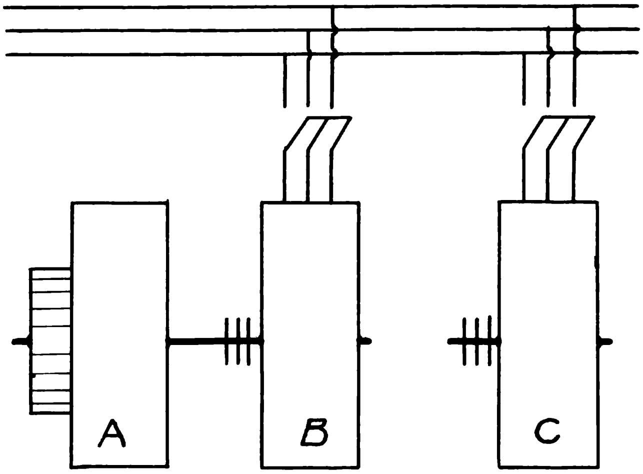

Figure 3.

account of its outstanding objections, most important of which are its high first cost, low efficiency, poor power factor, poor utilization of material, and large speed steps which are impracticable to change while the system is in operation.

The last mentioned disadvantage is removed by the use of direct current. In this, speed variations are made by changing the frequency applied to the primary of the driving motor operating as an ordinary induction motor. It need be said that this method is little better than the one previously described.

A much simpler and satisfactory method is to make use of a direct-current driving-motor A and an alternator as shown in figure 3. The speed variations of the main induction motor C are obtained by changing the frequency of the voltage delivered to the induction motor by the alternator. This is made possible by virtue of the dircet current motor A. This system is rather objectionable due to the fact that the generating set must be of relatively large capacity in order to accommodate the driving motor C.

Another method of accomplishing the same results, and the one most generally used, is made possible by an arrangement shown in figure 4. This system corresponds to the one just described except that the alternator B is replaced by an induction motor the secondary of which is direct-connected to the primary of the main driving motor C thereby serving as the source of power for that motor. The primary of the induction C is connected directly to a constant supply line. The operation of the system is based on the theory that the frequency of the current delivered by motor B to motor C depends on the relative speed of the rotor

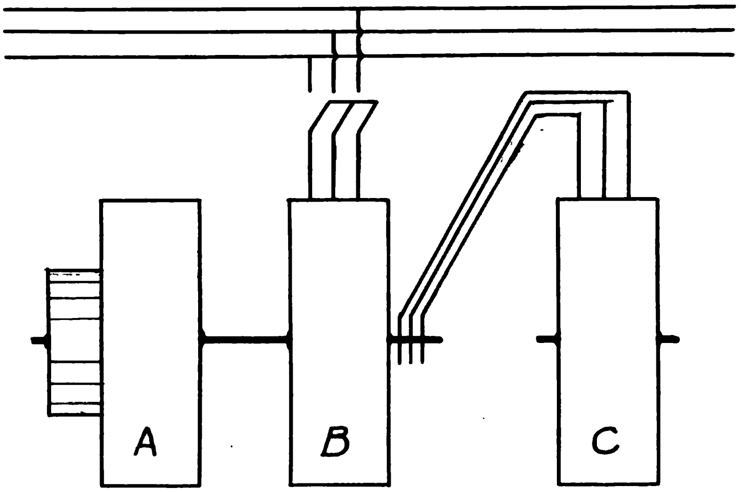

Figure 4.

of motor B to its synchronous speed; the slower the rotation of the rotor, the higher will be the frequency of the current delivered to C and, consequently, the higher speed of C. The speed of motor B is controlled by proper adjustment of the field of motor A. Motor B must be practically the same size as motor C; but motor A can usually be relatively smaller, the exact size depending upon the frequency range and the power required by motor C. This method is limited to service demanding constant torque with small speed variation, beyond which the cost, which is already high, becomes prohibitive.

There are several other systems hinging on the frequency changing principle, but most of them have a very limited application due to their extremely complicated and expensive features.

Multispeed motors: Theoretically it is possible to obtain practically any number of speeds required for a single motor by using two or more separate primary windings, each having a different number of poles; or by employing a single winding which can be connected so as to form different numbers of poles. The latter arrangement is shown diagramatically in figure 5.

In practice, however, either of these schemes is limited to one or two combinations, not only on account of the complexity of the motor design and the uneconomical use of material, but also because of the complication involved in the control apparatus. Four speeds is about the maximum number that can be obtained in practice with multispeed motors, and even this range requires an extremely complicated control equipment, especially if the motor is of the wound-rotor type. Two of these speeds need not be

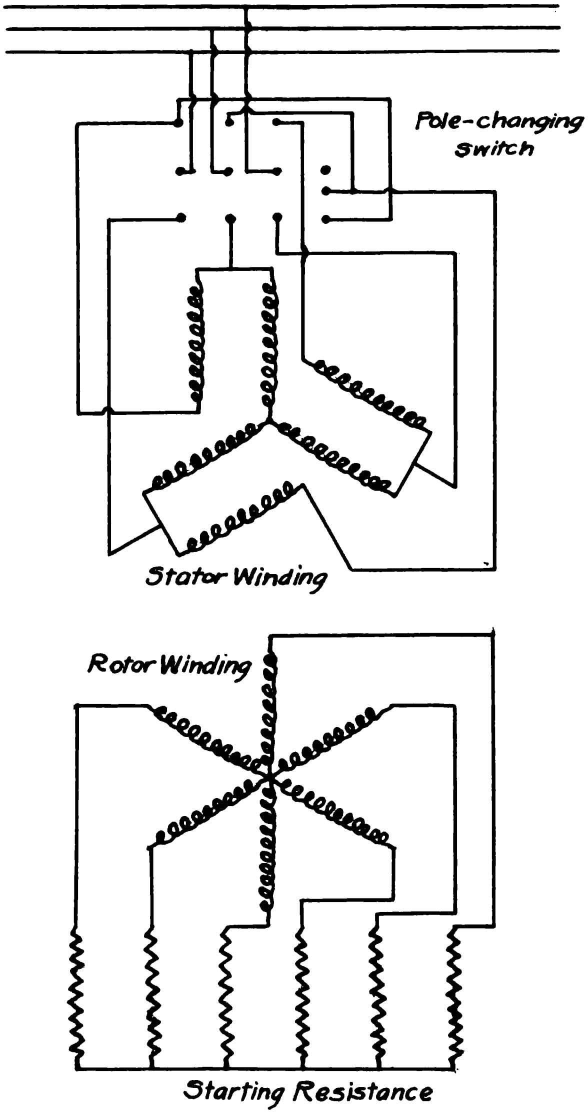
Pole-changing switch
Stator Winding
Rotor Winding
Starting Resistance

Figure 5.

definitely related to each other, but the other two must each be one-half of the corresponding higher speeds. Such an arrangement requires two windings of the stator; and, if a wound-rotor is used, necessitates two windings on the rotor, in either case each winding being grouped to give double the number of poles for the lower speed. An idea of the complications involved may be had from the fact that, in order to obtain the various combinations, such a motor must have at least nine slip-rings and twelve leads must be brot out from the stator. Because of the difficulties encountered in reconnecting the windings of a wound-rotor for the different speeds, a squirrel-cage rotor, which is adapted to any number of poles, should be used wherever practicable. When two windings are used on a squirrel-cage motor, the control resolves itself into the simple operation of changing from one winding to the other by means of double-throw switches. The practical combinations, however, are likewise limited to two speeds, beyond which the winding becomes extremely complicated.

The method of pole changing requires a complicated and expensive controller, but the efficiency and power factor of the combination is not very much lower than a single-speed motor of the same characteristics. From a practical operating standpoint the multispeed motor, under most conditions, gives suffecient speed range and is one that has been very extensively used under American conditions of rolling mill drive.

Cascade or Concatenated Control: The operation of two or more motors in cascade affors, under some conditions of service the most convenient and economical method of speed variation for

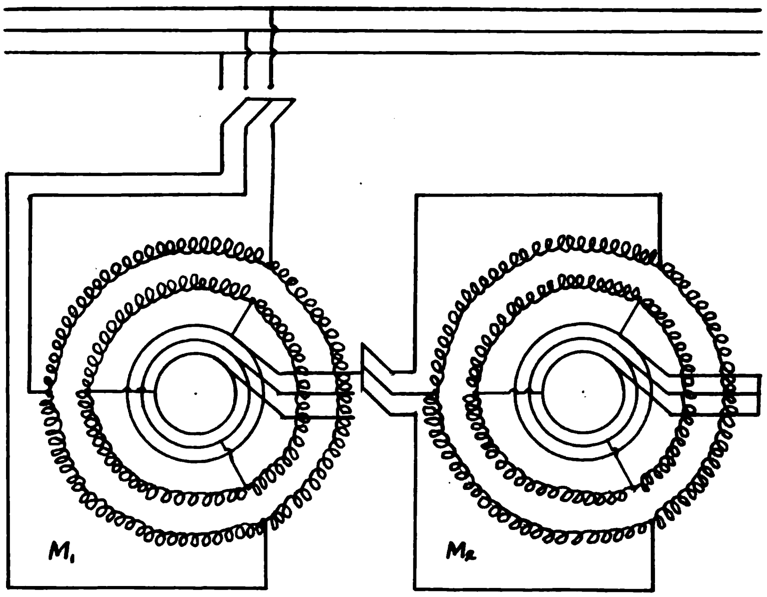

Figure 6.

induction motors. In this arrangement all the motors are mounted on the same shaft or their several shafts are rigidly coupled together so that they all revolve at exactly the same speed. The primary of the first motor is connected to the line, its secondary, which must be of the phase-wound type, is connected to the primary of the second motor, and so on. The secondary of the last motor may be either of the phase-wound or squirrel-cage type as the case may require.

Speed changes are made by changing the connections of the motors, the following combinations being possible with two motors: first, either motor can be operated at its synchronous speed with its primary connected to the line, with the other motor running idle; second, the motors may be connected in cascade so that their rotors tend to start in the same direction (direct concatenation, see figure 6) in which case the motors will run at a speed the same as would a single motor with the same number of poles as the two motors together; third, the motors can be connected in cascade so that their rotors tend to start in opposite directions (differential concatenation, figure 7) in which case the speed of the set will be that of a single motor having a number of poles equal to the difference of the number of poles of the two motors.

In the rotor of the second motor in either of the above combinations is of the phase-wound type, resistance can be inserted between the slip rings to obtain speed variation between the different concatenated speeds. Further, by providing each motor with pole-changing windings, obviously, the number

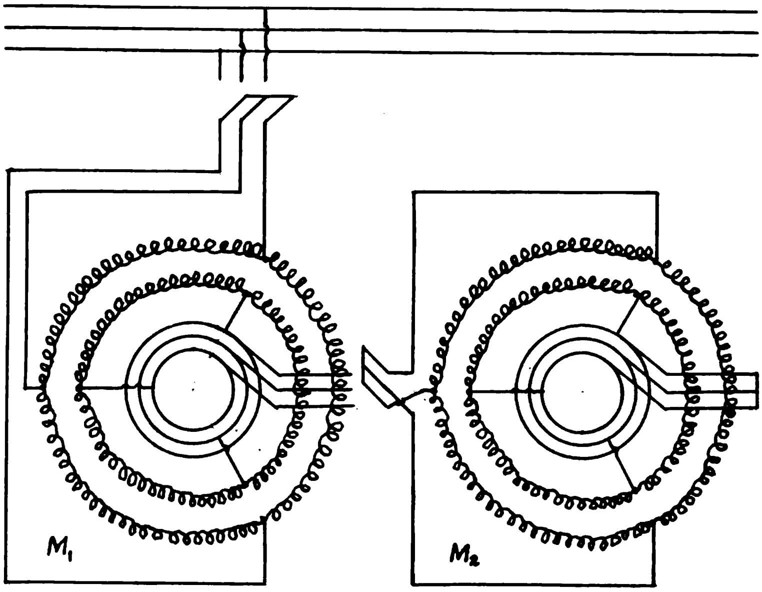

Figure 7.

of speeds may be greatly increased. This latter scheme, however, is not practicable even were it desirable.

From what has been said it would seem that with motors in cascade it is possible to obtain almost any number of speeds that may be desired. Actually, the number of speeds that can be obtained is limited by the cost of the equipment and the complications involved in the control apparatus more than by any limitations of the system. The combinations that are really practical do not give any greater range than can be obtained with multispeed motors. The poor utilization of material and low power factor are, probably, the most objectionable features, especially in rolling mill work where induction motors are so largely used. Among the desirable features possessed by the cascade arrangement might be mentioned the simple and safe control made possible by the requirements of relatively few leads and the total absence of main line switching operations for most of the speeds. In general, a cascade set possesses advantages in places where speed changes must be made frequently at high horse power output and primary voltage, and where the speed range is other than 2:1.

The cascade arrangement has been used to a slight extent in this country and to a greater extent Abroad, but on account of its high first cost and rather unsatisfactory operating characteristics, it has not found many advocates. Experience with speed requirements in steel work has shown that, on the whole, multispeed motors give better service than do cascade arrangements, and for this reason the multispeed motor has, in most cases, displaced the cascade arrangement in steel mill

work where moderate speed regulation is required.

CHAPTER II

Early Regulating Systems

General: The desirability of obtaining a greater speed range, economically, than was possible with the arrangements described in the previous chapter, caused sone of the European Manufacturers to experiment at an early date with some of the different arrangements involving the use of induction motors in conjunction with three-phase commutating machines. In all of these systems the energy from the rotor circuit is absorbed by an auxiliary machine, or machines, instead of being wasted in a rheostat as was the former practice, which auxiliary machine then delivers power to the system. By the adoption of such an arrangement it is possible to obtain regulation below synchronism; and, further, if energy is delivered to the rotor circuit by an auxiliary set, regulation above synchronism may also be obtained. By means of such an arrangement it is possible to combine many of the desirable features of the induction motor with those of the adjustable direct current motor. In addition to the wide range of speed made possible by the use of three-phase regulating machines, it is possible, with suitable arrangements to compensate for the power factor of the main induction motor and thus overcome the objections that are so often raised as to the use of induction motors on account of their low average power factor.

European Form of Kramer System: One of the first methods used for obtaining speed regulation of induction motors by means of commutating regulating machines was developed in Europe by Mr. Kramer. This system has worked fairly satisfactorily and has

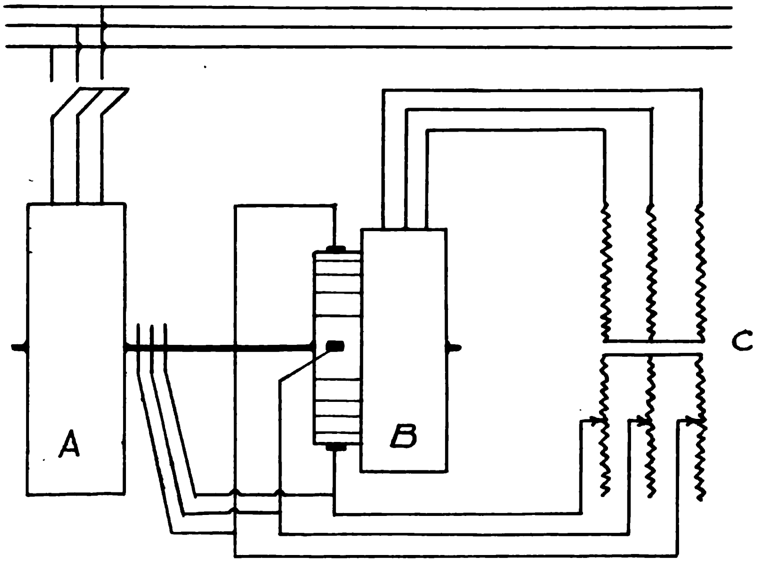

Figure 8.

been used extensively Abroad and to a lesser extent in this country. Originally this system had the commutator machine direct-connected to the main induction motor as shown diagramatically in figure 8. The main motor A, which is of the slip-ring induction-type, is designed to carry the full load. At this load the main motor is operating at nearly synchronous speed and so the auxiliary motor B is not loaded and, consequently, may be disconnected from the line. Speed reduction is accomplished by adjusting the variable secondary of transformer C so that the voltage will be boosted sufficiently to overcome the back e.m.f. of the auxiliary motor B.

Any increase in the voltage of motor B will cause a corresponding decrease in its speed, with the result that the energy from the rotor circuit, instead of being lost in a resistor as with rheostat control, is absorbed by the auxiliary motor which then assists the main motor in carrying the load. Within reasonable limits of speed regulation the auxiliary motor is comparatively small, although its capacity is determined by the percentage of speed regulation required. That is, if a speed reduction of 40 per cent is required, then, the capacity of the auxiliary motor must be 40 per cent of that of the main motor.

This system of speed regulation has the advantage that as the speed of the set is reduced the total available torque for the same line current is increased, in as much as the work done by the commutator motor increases directly in proportion to the decrease in speed. The set thus yields the same total kilowatt output at low speed as at normal speed. The disadvantage of the system is that the direct connection of the commutator motor

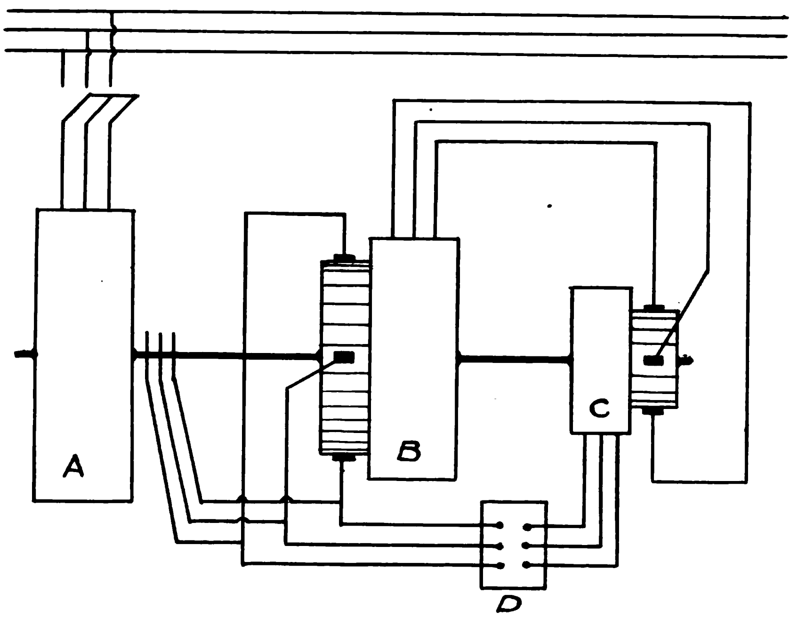

Figure 9.

necessitates it being designed for the same speed as the main motor, which introduces difficulties in construction of the auxiliary motor due to the relatively slow speed of the main motor.

American Modification of Kramer System: The Kramer method of speed control has been used quite extensively in American conditions of rolling mill practice although in a somewhat modified form of the one just described. A small direct-connected polyphase exciter similar in design to the auxiliary regulating machine is substituted for the transformer. The stator of this exciter C is supplied with energy from the slip rings of the main motor A thru a three-phase resistor D, as shown in figure 9. The operation of this system is similar to the one previously described except that the speed regulation is obtained thru proper manipulation of the resistor. This arrangement has a slight advantage over the European form in as much as a better speed regulation is made possible by virtue of the large number of running points available — a feature not abtainable with the transformer arrangement.

Scherbius System: A method of speed control which has certain advantages over the Kramer system and one which is well known in American circles is known as the Scherbius system after its inventor Mr. Scherbius. This system, as seen from figure 10, differs from the Kramer system in that the commutator motor B is not connected to the main motor mechanically, but is coupled to an induction machine D which is connected to the line. In this system, the energy from the rotor circuit is not transmitted to the shaft of the main motor, as in the Kramer system, but is

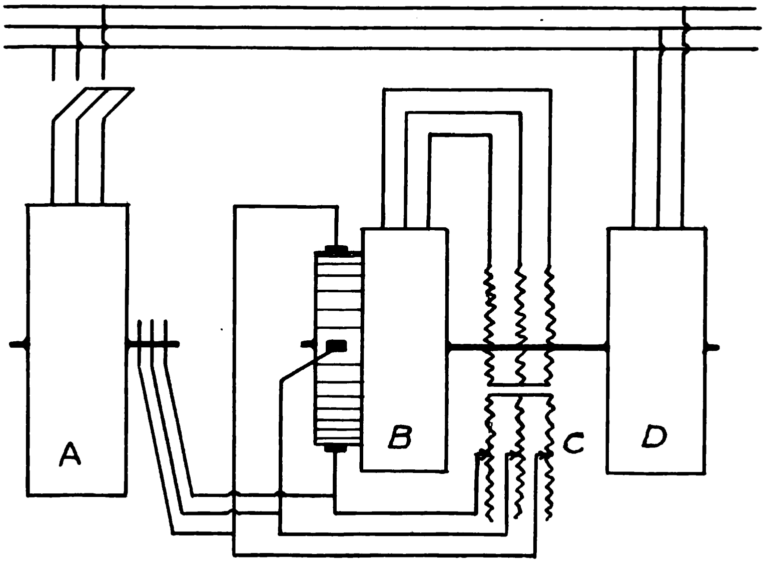

Figure 10.

transmitted thru the auxiliary machine and then returned to the line in the form of electrical energy. By providing the commutating motor of this arrangement with a compensating winding on the stator to counteract the rotor field it is possible to regulate the speed by varying the magnetizing current, and thus require only a small controller and regulating transformer. It is possible, further, to eliminate the transformer entirely if the machines are each provided with an auto-transformer winding.

Compensation for power factor in this system is obtained by means of a special phase combination somewhat different from that used with the Kramer system. This compensator provides correct compensation for only one definite speed and load, which are chosen so as to approximate, as nearly as possible, the average working conditions.

The chief advantage of this system over those previously described centers in its adaptability to work demanding constant torque. The one objectional feature of this system is that two auxiliary machines are required in order to obtain reasonable speed regulation. This undesirable feature is removed, however, in the modified forms of this system to be discussed later.

Heyland and Ruedenberg System: A system developed by Heyland and Ruedenberg and one use quite extensively in Europe is shown in figure 11. In this system the second auxiliary machine D is connected to the line and drives the frequency changer B against its mechanical losses. The stator of the three-phase rotary converter B is wound only with an auxiliary winding for improving commutation of the machine. The machine B, due to

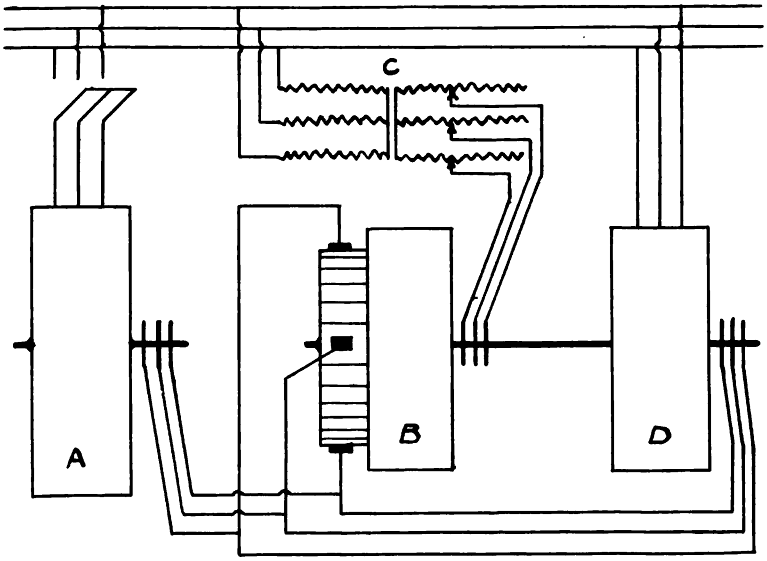

Figure 11.

~~to~~ the absence of a stator winding, cannot develope any torque and it is, therefore, necessary to employ the small auxiliary motor D to rotate it relatively in synchronism with the main motor A. Because of its position the regulating transformer C must be designed for the full energy of the rotor which flows thru the frequency changer and the transformer to the line.

This system has the disadvantage that the power factor cannot be regulated. This is not such an undesirable feature in as much as the power factor is fairly good, due to the favorable distribution of the magnetizing current. The chief advantage of the system over those previously described is found in the fact that it is possible to supply energy to the rotor circuit so as to obtain regulation above synchronism. The feasibility of dividing the regulating range of the motor above and below synchronous speed makes possible the use of an auxiliary machine only one-half the capacity of that necessary where the whole of the regulation was done below synchronism. In addition this system presents certain advantages when a speed higher than normal is required for a short period of time, in as much as the motor may be driven above synchronism when this is necessary.

All the systems employing commutator regulating machines thus far discussed, present many disadvantages, especially under American conditions where 25 cycles are the standard frequency for heavy power work. Not only is the construction of such systems difficult, but their cost is too great to warrant general commercial adoption. With the idea of overcoming these objections several ingenious arrangements, each a modification of the above systems, have been worked out; the essential features of these

will now be considered in their sequence of bearing to the above described systems.

Miscellaneous Systems: An arrangement which has been extensively used because of its particular suitability for mining and rolling mill work is shown diagramatically in figure 12. It will be noted that the arrangement is quite simple. The stator of the auxiliary frequency changer B is provided with a three-phase winding, each phase of which is connected to a small regulating resistance D. In addition the stator has an auxiliary winding to improve commutation. The primary of the regulating transformer C is connected to the line; its secondary is provided with three adjustable taps which are connected to their respective slip rings on the frequency changer. By means of this individual arrangement of the resistance and transformer it is possible to control the power factor and speed in two distinct ways. The operation of the system may be explained as follows:
The main induction motor A is started in the usual way as an ordinary induction motor with the connection to the frequency changer B open. The frequency changer is then started as follows: The rotor BR is supplied thru the regulating transformer C with voltage corresponding to the desired voltage on the rotor of the main motor; the stator winding BS, which is in this case the secondary, is regulated by means of the resistor D until the machine B operates relatively in synchronism with the main motor A. Now the frequency of the current in the rotor of the main motor is the same as that in the commutator and the stator of the frequency changer B, so that by means of synchronizing lamps, or other synchronizing devices, between the commutator of the

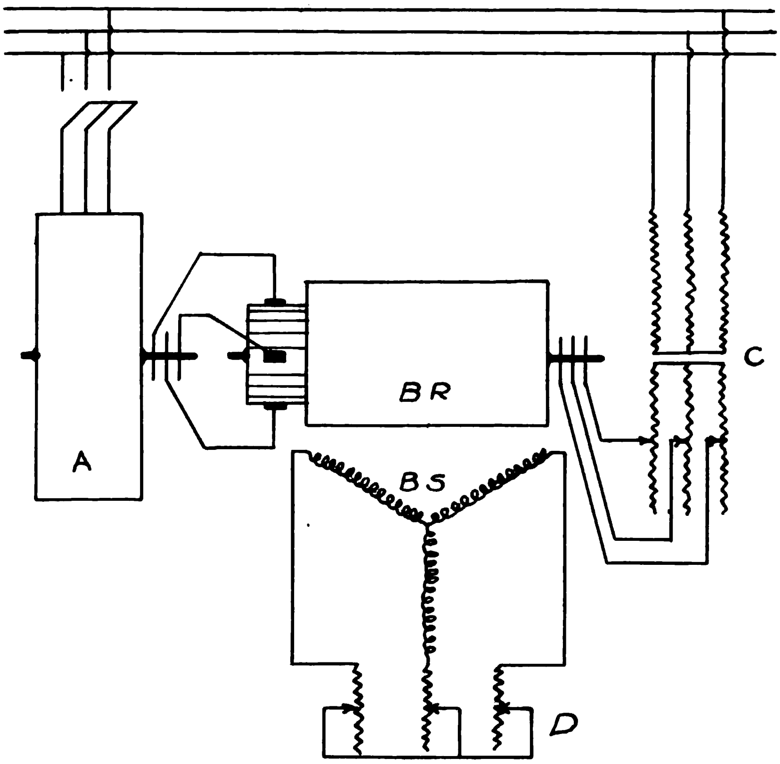

Figure 12.

frequency changer and the slip rings of the main motor, the two machines may be readily synchronized. Such devices are, however, rarely necessary in practice to synchronize the two machines. By adjusting independently either the resistance D in the stator circuit or the taps on the transformer C, power factor compensation of the whole system is possible so far as may be desired. For example, any reduction in the resistance D without changing the ratio of the transformer C would tend to increase the speed of the frequency changer, but an increase in speed is impossible because the rotor is mechanically coupled to the main motor, consequently, a synchronizing force is established by the equalizing current which flows in the circuit connecting the two rotors. By suitable regulation, then, of this circulating current the power factor of the whole system can be adjusted to any desired value. The speed of the set will fluctuate somewhat while this adjustment is being made due to the fact that the voltage drop in the two machines varies with a change in the wattless current, but this variation is only slight and causes no serious objection.

The system just described has several commendable features. Simplicity in construction and arrangement is made possible by the use of a single regulating machine instead of a number of such machines as were used in the systems described in the early part of the chapter. Furthermore, the regulation is easily accomplished by the adjustment of a transformer in any convenient way, or by means of an induction regulator which would avoid handling the regulating current entirely. Finally, the control of the system is fairly accurate in as much as the current in the stator circuit is very small and, therefore, need not be regulated

in fine steps.

In places where low voltages are practicable it is possible to eliminate the regulating transformer, just referred to, by the substitution of an arrangement similar to that shown in figure 13. In this system, as in the previously described one, we have also the main induction motor A and the frequency changer B with its rotor R and stator S. The slip rings are connected across the line; and the three leads from the commutator brushes are connected each to a leg of an adjustable auto-transformer winding which is combined in the machine as a part of the stator. Now the stator winding is also connected by means of adjustable taps to the slip rings of the main motor, so that is possible to regulate both the speed and power factor of the system in two distinct ways just as in the system previously described. If the two machines are connected electrically and are operating relatively in synchronism, then the power factor can be regulated by adjusting the stator winding in such a way as to leave the transformer ratio unchanged while the absolute number of active turns is varied sufficiently to cause the proper change in wattless current. The magnitude of this current is comparatively small so that the regulation may be done with a single controller, simple in design and with but few steps.

The above system possesses many of the desirable features essential to good rolling mill practice, in as much as it does not require any change in the arrangement or connection of the windings on the machine, or necessitate shifting of the brushes, or require the insertion of gearing between the main motor and auxiliary motor in order that a regulation of power factor may be

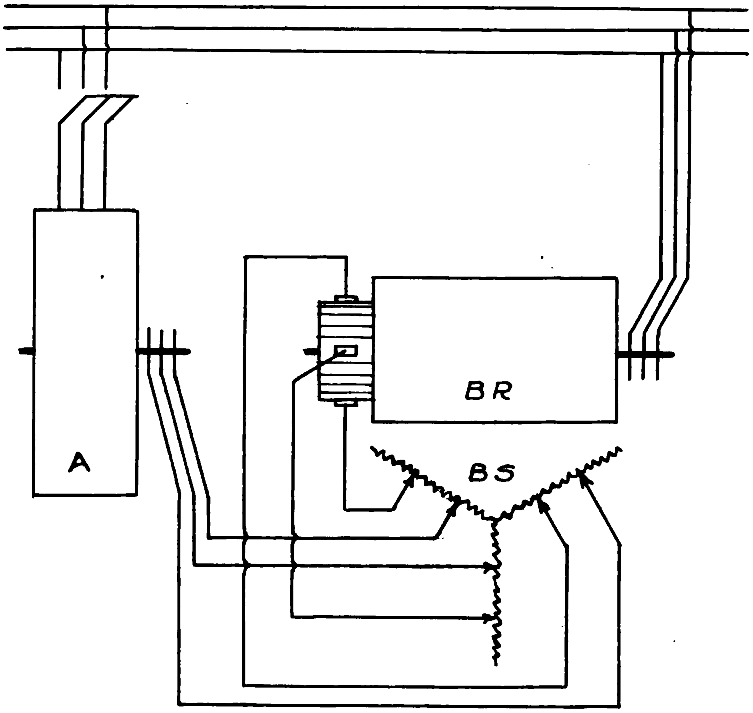

Figure 13.

obtained. Furthermore, the auxiliary motor combines in itself all the regulating requirements and is therefore, voltage regulator, frequency changer, power factor compensator, and motor for driving itself. Finally, it is possible, by various arrangements of the apparatus, to operate equally well above synchronism as below with no attended difficulty in passing thru synchronous speed.

This system just described is particularly suitable for regulating the speed in fairly large steps under conditions such that the main motor operates at a speed that does not require the services of the auxiliary motor, in which event the latter may be disconnected and used to regulate the power factor. When it is necessary to operate near or at synchronism, however, it is much better practice to make use of an arrangement as shown in figure 14. This system provides for an almost constant working field under all conditions and is for this reason is especially suitable for regulation in fine steps near the synchronous speed. This system is desirable where close speed regulation is required, where size and expense of the machine do not determine the type, and where technical reasons make it desirable to employ such an arrangement — for example for driving turbo-compressors or blowers, which generally run at very high speed and where the power demanded varies practically as the cube of the speed.

The regulation of the above system is obtained in a way very similar to that of the system shown in figure 13 in as much as the stator has two adjustable taps per phase. Operation above synchronism is made possible by means of a continuation of the phase winding thru the star of the stator. This arrangement

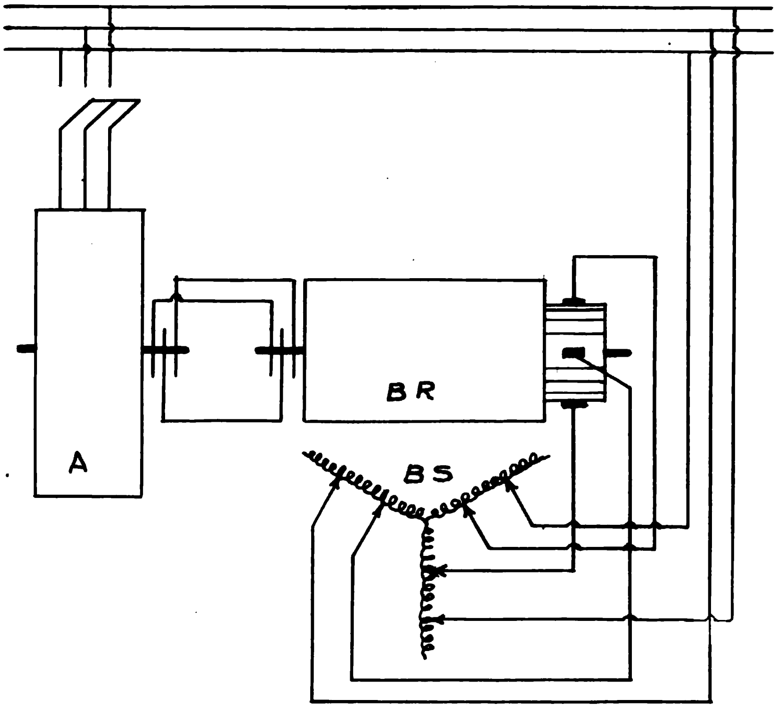

Figure 14.

was objectionable formerly in as much as it created an unsymmetrical phase arrangement. This feature is no longer a serious one because of the great improvements that have been recently made in three-phase commutating machines.

CHAPTER III

Recent Regulating Systems

Synchronous Converter Method: The permissable range of speed regulation with all of the methods thus far discussed is limited by the maximum frequency that can be successfully applied to the regulating motor without objectionable commutation difficulties. In general this frequency should not exceed 18 to 20 cycles (approximately 30 per cent regulation) on a 60-cycle circuit, and from 10 to 12.5 cycles (approximately 50 per cent regulation) on a 25-cycle circuit. Where greater ranges are required or with units involving a very large slip energy, say 1,000 kilowatts or more, a synchronous converter and direct-current motor, as shown in figure 15, can sometimes be substituted to advantage for the polyphase commutator motor. By means of this arrangement the slip energy of the main motor A, at varying frequency and voltage, is transformed to direct current at proportional varying potential by the synchronous converter B. This direct current shunt motor C, which may be mounted either on the shaft with the main motor as in the Kramer system, or may form one unit of the motor-generator set CD as in the Scherbius system. D is an ordinary induction motor which, when driven above synchronism, acts as an induction generator and returns to the system the slip energy of the main motor, less of course, the losses in the rotary converter and motor-generator set.

This system will give practically any range of speed regulation and is one that has been widely used in this Country

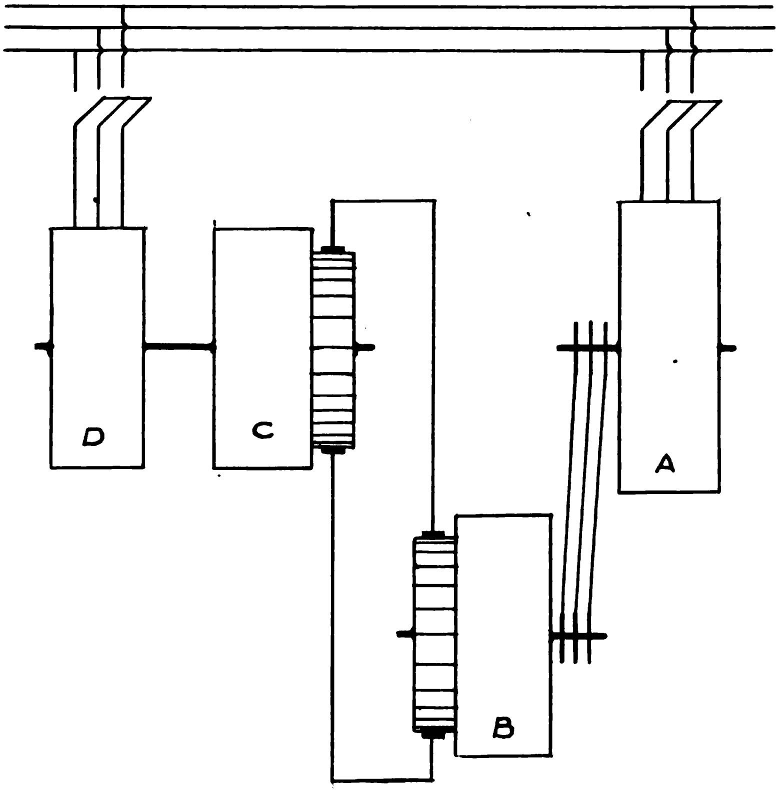

Figure 15.

during recent years. It is especially useful on 60-cycle systems, not only because of the total elimination of commutation difficulties encountered with commutator motors, but also because the objections arising from "hunting" of the synchronous converter are less on 60-cycle than on 25-cycle circuits. If suitable mechanical devices are employed to control the speed of the synchronous converter during the unstable period of minimum frequency about synchronous speed, the converter may be operated inverted and thus obtain regulation above synchronous speed.

Modification of Scherbius System: The most satisfactory method yet devised for the economical speed control of induction motors used for rolling mill drive comprises a recent modification of the original Scherbius system which was described in Chapter II. By means of this system double-range regulation is possible in as much as operation is permissible both above and below synchronism.

An idea as to the general arrangement of the system may be had from a study of figure 16. The main roll motor A comprises the usual type of three-phase machine with a phase-wound rotor and has its stator connected to the line. The regulating set consists of an induction generator B, a regulating motor C, and an exciter D all of which are mounted on a common shaft. The induction generator is a squirrel-cage machine which may be operated either above or below synchronism. When it is driven below synchronism it acts as a motor drawing power from the line. When it is driven above synchronism it acts as an induction generator and delivers power to the line. The regulating motor is a polyphase commutator machine provided with an armature

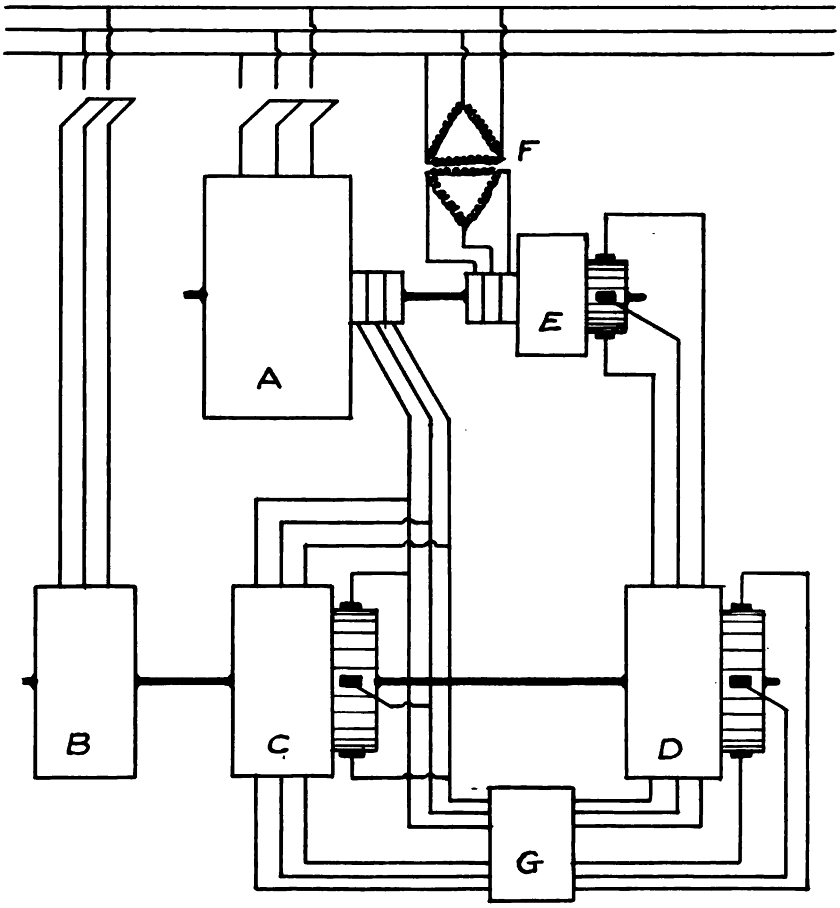

Figure 16.

similar in design of that of a direct current machine. Its stator usually comprises three distinct windings; a compensating field, winding, an interpole field winding, and a main exciting field winding. The exciter is similar in design and construction to the regulating motor except that reduced capacity and lighter service somewhat simplify it.

In addition to the regulating set the system requires a small auxiliary exciter E which has been named an ohmic drop exciter. The armature of this machine is mounted on the same shaft with the main motor so that it will rotate at exactly the same speed as the larger motor. This little machine is capable of supplying a constant voltage at varying frequency, this frequency being always the same as that in the secondary of the main motor. Because of this fact the exciter must be wound with the same number of poles as the main motor.

The armature of this exciter E is comparable to that of a rotary converter inas much as it has both slip rings and a commutator with brushes. The field which surrounds this armature, however, is free of all slots or windings. Now the slip rings of this machine, as shown in the diagram of connections, are connected thru a three-phase transformer F to the line. By means of this arrangement a variable voltage is impressed upon the slip rings which, with the armature at rest, sets up a magnetic field by virtue of the current flowing in the field coils, which magnetic field revolves around the rotor at a speed depending on the frequency of the voltage and inversely upon the number of poles, just as in the case of an ordinary induction motor. Now if the main motor be operated at synchronous speed, and the phase rotation of

the magnetic field in the ohmic drop exciter should happen to be apposed to the mechanical rotation, then the magnetic field would no longer rotate but would remain stationary with respect to space. The rotating armature conductors would then cut this stationary flux at synchronous speed, which would generate a voltage and cause the exciter to act similar to a direct current generator delivering power from its brushes.

When the main motor is operated at one-half synchronous speed, the armature of the exciter and the magnetic field both rotate at half speed, with the result that the flux is out at the same rate thus generating the same voltage as existed under synchronous conditions and at standstill. The frequency in this case would be one-half of the normal frequency applied to the slip rings of the ohmic drop exciter, or exactly the same as the frequency of the secondary of the main motor. At any other speed the voltage generated is constant, and alternating current at a frequency equal to that in the secondary circuit of the main motor is delivered from the brushes of the exciter E.

The exciting winding of the regulating motor C is a shunt winding and is connected directly across the slip rings of the main induction motor A. This arrangemnt yields a constant flux in the field irrespective of the change in load on the main motor, because as the speed of the main motor fluctuates with load, the voltage and frequency also vary proportionately, thus leaving the flux unchanged.

By a series arrangement of the exciter armature and the field of the exciter, it is possible to have the exciter buck or boost

the slip-ring voltage just sufficiently to supply the requisite percentage to the field of the regulating motor. For example, if it is desired to operate at a speed requiring one-half of the slip ring voltage impressed on the field of the regulating motor, the exciter must automatically buck the other half of the voltage. The machine must therefore be capable of generating a voltage always proportional to the slip-ring voltage instead of a constant voltage like that supplied the regulating machine. This is made possible by the use of an unsaturated shunt machine in which the voltage is proportional to the field current. By exciting one of the fields directly from the slip-rings of the main motor over a resistance which is large as compared to the reactance of the circuit, a field current is obtained that is practically proportional to the slip-ring voltage. Now any change in this exciter-field resistance causes the exciter to consume a different proportion of the slip-ring voltage, thus altering the field of the regulating motor which in turn changes the speed of the main motor.

It will be noted from the diagram that one of the two fields of the exciter is excited from the ohmic drop exciter. It is the function of this field to balance the ohmic drop in the field circuit of the regulating motor by virtue of the voltage generated by the ohmic drop machine. This field plays little or no part in the speed variation under conditions remote from synchronism, but assumes more and more importance as synchronism is approached until synchronism is reached when it must provide all the required excitation.

Under actual operating conditions the double range reg-

ulating systems presents several decided advantages.

Flexibility: Maximum effeciency is obtained with this system even when the main motor is run non-regulating at its average speed. This is not possible in single-regulating systems in which the maximum efficiency corresponds to the maximum speed.

Maintenance: It is possible to minimize wear and upkeep of the regulating sets while rolling at non-regulating speeds.

Production: In event of trouble with the regulating set, it is possible to toll a wider variation of sections with the main motor operating alone than is possible with single-regulating systems under similar conditions. It is further possible to roll high speed sections at the average speed with reduced tonnage, a feat impossible with single range systems operated non-regulating.

Running points: Almost any number of running points up to one hundred or more can easily be obtained by means of this system.

Power Factor: The system offers easy and convenient means for power factor compensation.

Asynchronous Apparatus: In as much as there is no synchronous apparatus in the system there is no tendency for any of the machinery to fall out of step under conditions of sudden fluctuation in load.

CHAPTER IV

Starting and Controlling Apparatus

General: In the control of induction motors in conjunction with speed-regulating sets, the function of proper seguence of operation is of utmost importance. If there are several individual machines, and considerable auxiliary equipment in the system, each device must be connected or disconnected at the proper instant to prevent damage to some of the rotating or control apparatus. Therefore, it is usually advisable to provide magnetic control, for this type easily accomodates the incorporation of interlocking medium that enforces proper handling of the equipment, even by rather inexperienced operators. Magnetic control, however, is not essential in all cases; for small motors can be controlled almost as easily by means of hand-control provided with a few auxiliary contractors. This latter type of control is, however, particularly applicable to cases where speed changes are infrequent, such as in motor installations driving mine fans and pumps where a single speed reduction extends over a considerable length of time.

Experience with control conditions in connection with induction motor drive seems to indicate that, on the whole, even in connection with small motors used for comparatively simple service, magnetic control is advisable for one or more of the following reasons: (1) because manual controllers would be of such size as to require excessive physical exertion in their operation; (2) because the high operating voltages require that the control apparatus bearing line potential be remote from the operator; (3) because the complicated nature of the control

equipment requires that it be automatic, thus removing from the operator all care in connection with the sequence of operation; and (4) because the continuous operation of the machinery requires the application of limit switches, speed limiting devices, and other safety features all of which are so easily adapted to magnetic control.

Starters for Squirrel-cage Motors

Compensator Panel: Of the two types of induction motors, probably, the squirrel-cage type is the most largely used in rolling mill work, because the simplicity and ruggedness of its consruction commend its use where experienced electrical attendants are not available. Altho this type of motor is mechanically strong enough to withstand the sudden shock when full voltage of the supply mains is applied to its stator, yet it is imperative that some starting device be used to eliminate the detrimental disturbances on the line caused by the sudden inrush of the heavy starting currents. The method most commonly used to accomplish this end is to reduce the supply voltage from 50 to 70 per cent of its normal value by means of a transformer. The fundamental features of this method have been centered in an automatic compensator panel by means of which a motor can be started automatically. This apparatus constitutes a two-pole line contractor, a current limit relay, a four-pole line starting contractor, an auto-transformer, and the necessary control circuits.

The current-limit relay used in this arrangement is composed of a shunt coil and a series coil, the latter of which makes contact with the line during starting. The plungers of these coils

are supported one on each end of a lever pivoted at its center, and are so proportioned as to cause the series coil, under normal conditions with both coils de-energized, to be raised. The series plunger in this position acts upon a contact lever above the relay which normally make contact with two studs, but makes contact with the lower stud when the plunger of the series coil is allowed to drop. Immediately below the relay is an auxiliary contactor which closes with the energizing of the shunt coil.

The actual connections of such a contactor panel are shown diagramatically in figure 17. Upon closing the contact switch, a circuit is established from the line thru the control switch, thru the contact lever of the current-limit relay to the upper stud, thru the operating coil of the starting contactor and a normally closed interlock on the line contactor on the opposite side of the line, and finally closing the starting contactor. This connects the compensator to the supply mains and allows the motor to start in connection with the low voltage taps. As soon as the starting contactor closes, the normally open interlock closes the circuit from one side of the line, thru the control switch, shunt coil of the current-limit relay, interlock on the starting contactor, to the other side of the line, thus energizing the shunt coil of the relay. As the shunt-coil plunger rises, the auxiliary interlock below the relay closes a holding circuit from the shunt coil that is independent of the interlock on the starting contactor, but which does pass thru the normally closed interlock on the line contactor. The energizing of the shunt coil leaves the series coil free to fall as soon as the starting current of the motor has decreased sufficiently — usually about

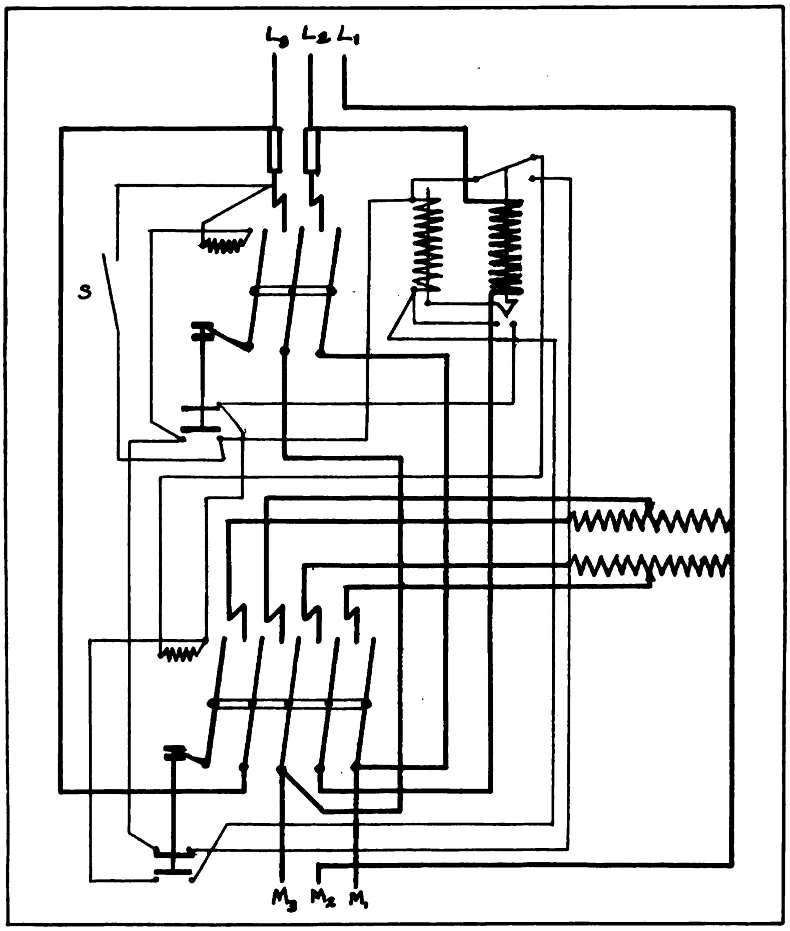

Figure 17.

25 per cent above full load value. When the series plunger drops, it causes the lever at the top of the relay to open the energizing circuit of the starting contactor, thus causing the latter to drop out. A circuit is now established from one side of the line thru the control switch, thru the lower control stud of the contact lever of the current-limit relay, thru the mormally closed interlock on the line contactor to the other side of the line, thus energizing the line contactor and connecting full voltage to the motor. As the line contactor closes it establishes an energizing circuit thru its own normally open interlock, and at the same time de-energizes the shunt coil of the relay. By causing the energizing current, which causes the contactor to rise, to pass thru the normally closed interlock on the starting contactor, it is necessary for the latter to open before the line contactor can close, thus making it impossible to connect both low voltage and line voltage to the motor at the same time. In as much as, under normal conditions of the panel, the energizing circuit is directly thru the control switch, it is only necessary to open that switch in order to open the line contactor and disconnect the motor from the line.

Resistance in Line: Another method commonly used to start squirrel-cage induction motors makes use of resistance inserted in series with the lines to reduce the starting currents taken by the motor. Altho this method is rather inefficient, yet it is satisfactory for motors of small sizes where low starting torque is permissable and heavy starting currents with corresponding line disturbances are not detrimental. The arrangement of such a system is pictured diagramatically in figure 18. It

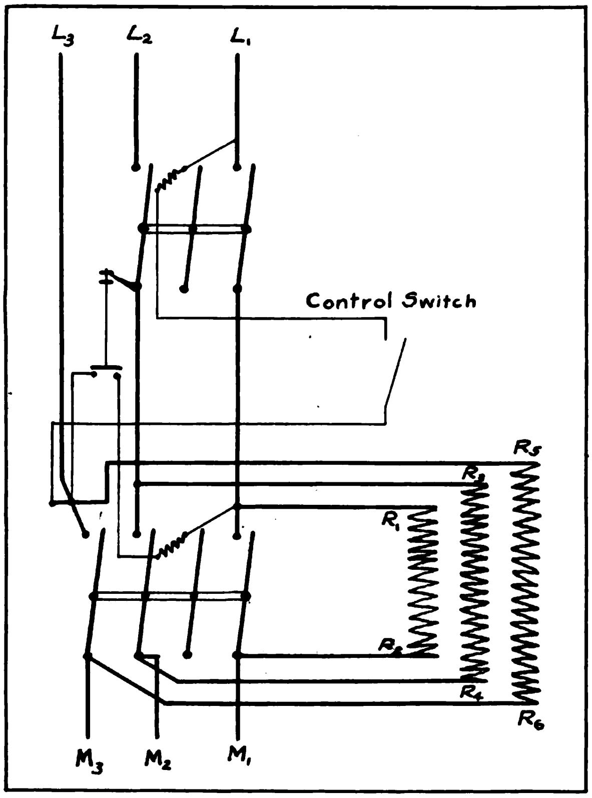

Figure 18.

consists of a two line contactor and a three-phase resistor provided with a three-pole contactor for short circuiting the resistances. The motor is connected directly to the line voltage by closing successilely the line switch and the three-pole contactor. The automatic acceleration of this operation is controlled by a time-limit dashpot, the plunger of which carries an interlock disk. This time-limit dashpot is so arranged in connection with the contactor that when the latter is open the plunger is held up. The closing of the contactor causes the plunger to fall freely, and, after a predetermined length of time depending upon the rate that air is allowed to flow into the dashpot, the interlock disk closes the contactor by making contact across two studs thus energizing the circuit of the three-pole contactor.

Starters for Form-wound Motors

Resistance in Rotor Circuit: In places where the wound-rotor type of induction motor is used, smooth acceleration is almost invariably obtained by means of an adjustable resistance placed in series with the rotor circuit, the various sections of which are cut out as the motor comes up to speed. A panel designed for this purpose usually embodies a line contactor, a resistor, a number of accelerating contactors so arranged as to short circuit the various sections of the resistance when closed, and one or several current-limit relays. The current-limit relay here used differs slightly from that used on the compensator panel in as much as the contact lever is replaced by a contact disk which is held open by the series-coil plunger when that plunger is held up and which also makes contact across two studs when the plunger is allowed to fall. The contact below the relay

is not required in this panel as was the case in the compensator panel.

Upon closing the line contactor of the panel, see figure 19, thru a control switch, the energizing circuit is completed and causes a normally open interlock to close. Now the shunt coil and the contactor are so proportioned that, when connected in series, the shunt coil will become energized and lift its plunger before the contactor can act. When the plunger of the shunt coil rises, it leaves the plunger of the series coil free to fall as soon as the current flowing thru it decreases to the predetermined value. The interlock carried by this plunger then short circuits the shunt coil of the relay, thus connecting the coil of the contactor directly across the line; this closes the contactor. The contactor is then held in position by means of a normally open disk which is mounted on the contactor and works independently of the current-limit relay. The second accelerating contactor is now connected across the line thru the shunt coil of the second current-limit relay to a normally open interlock of the first accelerating contactor. By the time the line current has again decreased to a value sufficient to cause the dropping of the series coil of the relay, the second contactor has closed, forming its own holding circuit just as was done by the first contactor. The third accelerating contactor is next closed across the line thru a normally open disk on the second contactor, this time as before making use of the first current-limit relay and closing when the current in the line has decreased to the set value. This closing process is repeated for all the following accelerating contactors, each being closed thru an interlock disk

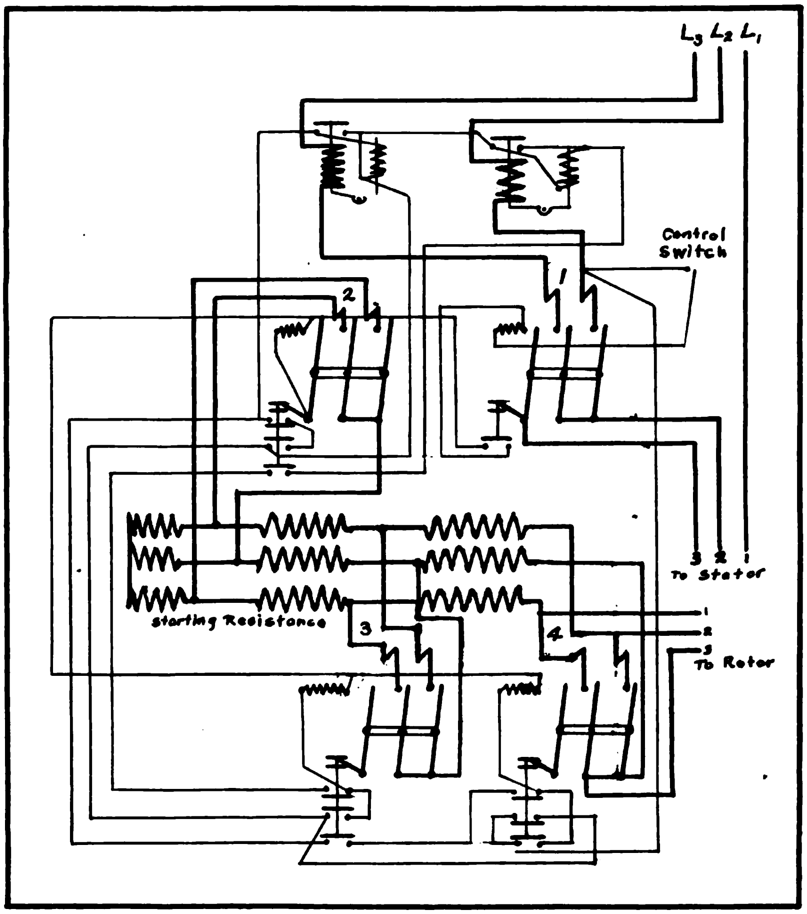
L3 L2 L1
Control Switch
2
1
Starting Resistance
3 2 1 To Stator
3
4
1
2
3 To Rotor

Figure 19.

on the preceding contactor and making use of the two current-limit relays. In as much as the magnetizing current taken by the coils of such a panel is large, the interlocking system is usually so arranged that the last accelerating contactors, which short circuit the rotor slip rings, are de-energized when the contactor is closed.

It is customary to provide panels of the above type with the overload protection in the form of inverse time-limit overload relays in two of the lines of a three-phase circuit and one in each of the lines of a two-phase system. These relays comprise a coil connected in series with the motor circuit, and a plunger the lower end of which travels in a dashpot of oil. The varing time-element is obtained by the regulated size of the opening thru which the oil must flow. The contact element is wired into the control circuit of the line contactor and is fitted with a toggle joint which gives it a snap-action break.

Time-limit Starter: Under some conditions of service — on a circuit which is subject to fluctuations in voltage, or where starting conditions vary considerable — it is sometines desirable to employ a starting panel of more positive action; that is, one in which the contactors will close in their proper sequence regardless of external conditions. This type of service is best handled by means of a time-limit starter, which, as in the panel for starting the squirrel-cage motor thru primary resistance, makes use of a dashpot interlock. A panel of this type is shown in figure 20. A study of the diagram will reveal the fact that this type of panel is much simpler than the type using current-limit relays in as much as in requires no complicated inter-

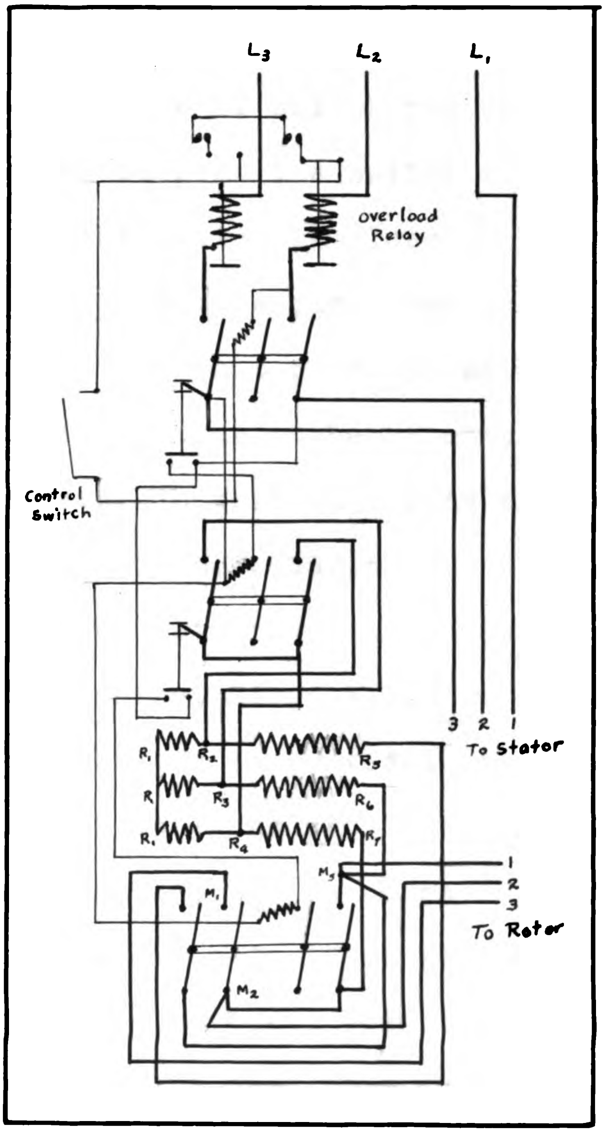
L_3
L_2
L_1
overload Relay
Control Switch
R_1
R_2
R_5
R
R_3
R_6
R_1
R_4
R_7
3 2 1
To Stator
M_1
M_3
M_2
1
2
3
To Rotor

Figure 20.

locking system.

Master Switches

Single-pole Type: In connection with each of the above described types of panels, there are several different types of master switches that may be used. The simplest of these makes use of a single-pole switch in the energizing circuit of the contactor coils. This type of switch reduces the control to the simple operation of closing the switch and the contactor remains closed so long as the switch is closed.

Push-button Control: A much more convenient form of hand-operated switch and one that presents several advantages over the single-pole type is know as push-button control. This type of control is much safer in that all parts are well covered. Moreover, its operation is more definite. Each station is provided with two buttons — one marked "stop" and the other "start". The "start" button closes the contact circuit of the panel thus starting the motor. The "stop" button is provided with a normally closed contactor which provides a holding circuit for the panel control. Since this circuit passes thru a normally open interlock on the line contactors of the panel, it is possible to stop the motor by merely pressing the button. This type of switch possesses two additional features that make it even more desirable. In the first place it is possible to use several control stations placed in convenient places, by connecting all circuits to the "start" buttons in multiple and all holding circuits to the "stop" buttons in series. A second advantage deals with a no-voltage protection. If the line contactor opens due to failure of voltage, the pick-up circuit can place the panel in operation again only after

the "start" button has been pressed. When several stations are used in connection with one machine, an additional safety feature in the form of a "safe-run" button may be used. This consists of a flush-type snap-switch with a circuit open when the "safe" button is in. Since all the circuits of such a station are wired thru a "stop" button, it is impossible for anyone to start the motor from any other station before the "run" button has been pressed at the station. This simple arrangement makes it absolutely safe for an operator to make adjustments about the machine without fear of the machine being started accidentally from some other station.

SUMMARY

A knowledge of the inherently constant-speed characteristics of the induction motor has revealed the fact almost from the first that if this type of motor was to be successfully applied to that phase of multispeed service encountered in rolling mill work, considerable modifications and improvements were due in the way of its starting and speed regulating spparatus. The former has long since become standardized and for this reason needs no further comment here. The latter, quite contrary, has always been a debated question and center of interest to electrical engineers. Combined and conscientious efforts on their part, however, have yielded a multitude of schemes and arrangements, some of them exceedingly ingenious, for the further solution of the multispeed problem.

The chief characteristics concerning the most important of these systems have been described in the past chapters as fully as the limited information at hand would permit.

The importance of the simpler and more commonly used of these speed regulating systems is indicated by the diversity of their application and the apparent success they have attained. But the more complex regulating sets involving the use of commutator machines in conjunction with the main induction motor are still subject to liberal criticism and repeated modifications. The desirability of such regulating sets, however, cannot be questioned; but, unfortunately, under the conditions existing in this country, there are certain difficulties standing in the way of their general adoption.

Altho regulating sets of the three-phase commutator type,

have been used for many years in Europe under the more or less ideal conditions existing there, and with apparent success; yet this state of affairs does not directly concern American conditions. Here the problem of adapting the induction motor to rolling mill drive has to deal chiefly with the education of that inferior class of labor that must be employed in many of the steel plants for the care and operation of these machines. And for this reason it is only after this preliminary difficulty has been removed, at least to a large measure, that it may be expected that these regulating systems will find more extended application. Recent improvements in speed-control apparatus, however, have contributed greatly to the simplification and direct solution of the multispeed problem. Moreover, most of the main characteristics of these newer regulating systems have already been tested out under the rather severe conditions of American rolling mill practice and have shown every indication of success. A proper interpretation of this meaning would, therefore, seem to indicate that the induction motor, so far as its satisfactory control and regulation are concerned, has nearly achieved its end.

BIBLOGRAPHY

A.I.E.E. Proceedings

Volume 32, January 1913.
Volume 32, March 1913.
Volume 34, February 1915.
Volume 34, May 1915.
Volume 34, November 1915.
Volume 35, May 1916.
Volume 35, June 1916.
Volume 35, October 1916.
Volume 35, December 1916.
Volume 34, April 1915.

Journal A.I.E.E.

Volume 29, 1900.
Volume 33, 1904.
Volume 39, 1907.
Volume 41, 1908.

A.I.E.E. Transactions

Volume 28, 1909.
Volume 29, 1910.
Volume 30, 1911.
Volume 31, 1912.

Elect. Ry. & W. Elect.

December 18, 1915.
January 22, 1916.
April 22, 1916.
November 11, 1916.
September 16, 1916.
May 6, 1916.

General Elec. Rev.

September 1916.
October 1916.
April 1916.
June 1914.

Electrical World

May 30, 1914
February 27, 1915.
August 14, 1915.
October 2, 1915.
October 16, 1915.
November 13, 1915.
September 9, 1916.
October 21, 1916
November 11, 1916.

Iron Age

May 15, 1913.
June 26, 1913.
December 4, 1913.
October 16, 1913.
October 12, 1916.
November 3, 1915.

Iron Trade Review

January 23, 1913.
January 30, 1913.
May 1-8, 1913.
May 22, 1913.
August 7-28, 1913.
December 4, 1913.
December 24, 1914.
April 29, 1915.
September 9-16, 1915.
November 11, 1915.
January 6, 1916.
May 18, 1916.
July 13, 1916.
August 31, 1916.

Power

February 25, 1913.
March 11, 1913.
October 14-28, 1913.
October 12, 1915.
December 2, 1913.
December 16, 1913.
April 27, 1915.
January 18, 1916.

APPROVAL

The foregoing thesis is hereby approved as a creditable study of an engineering subject, carried out and presented in a manner sufficiently satisfactory to warrant its acceptance as a prerequisite to the degree for which it has been submitted. It is to be understood that by this approval the undersigned does not necessarily endorse or approve any statement made, opinions expressed, or conclusions drawn therein, but approves the thesis only for the purpose for which it is submitted.

Approved M C Beebe
Professor of Electrical Engineering

June 15, 17

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